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EMPIRICAL PROCEDURES FOR PREDICTION OF ROCK FRAGMENTATION BY BLASTING

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by

Yves C. Lizotte *

ABSTRACT

This report presents empirical formulas and procedures for the prediction of rock fragmentation by explosives blasting. These procedures are based on field and laboratory experiments in which attempts are made to correlate resultant fragmentation to specific blasting parameters. The Kuz-Ram procedure, based on the Kuznetsov and Rosin-Rammler equations, is the most widely accepted procedure in use in the industry at present. A computer program which applies the Kuz-Ram procedure is described herein. Examples illustrate the potential use of the program. An annotated program listing and results are appended.

Key words: Fragmentation, blasting, prediction, Kuz-Ram

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PROCÉDURES EMPIRIQUES POUR PRÉDIRE LA FRAGMENTATION DU ROC PAR SAUTAGE

par

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RÉSUMÉ

Ce rapport présente les formules et les procédures empiriques pour l'estimation de la fragmentation du roc par sautages d'explosifs. Les procédures sont basées sur des essais sur le terrain et en laboratoire par lesquels on tente de corréler les résultats de fragmentation aux paramètres spécifiques des sautages. La procédure Kuz-Ram, basée sur les équations de Kuznetsov et de Rosin-Rammler, est la procédure la plus acceptée qui est utilisée dans l'industrie. Un logiciel qui applique la procédure Kuz-Ram est décrit. Des exemples illustrent l'utilisation potentielle du logiciel. Le logiciel annoté et des résultats sont annexés.

Mots clés: Fragmentation, sautage, prédiction, Kuz-Ram

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1. INTRODUCTION

The general process of rock blasting can be analytically modelled with fairly consistent accuracy. These analytical models consider the physical phenomena of pressure transients, strain waves and the thermo-dynamic properties of the explosives. The analytical models can be used to predict pressures, velocities of rock motion, potential throw, rock pile shapes, etc., with acceptable precision. However, the actual breakage surface must be empirically determined by field tests before the models are 'calibrated' for the simulation of a range of different modifications. In addition, mean fragment size and size distribution cannot be assessed directly with these models. The main difficulties appear to be the exact modelling of the interaction between the explosive and the rock, and the reaction of the rock mass subjected to dynamic load conditions. The difficulties are compounded when applying the analytical models to practical situations with heterogeneous rock masses and structural discontinuities.

Numerous benefits can be obtained from estimating fragmentation as a function of blast parameters, particularly when these estimates can be achieved with very few field tests. A fragmentation estimation procedure can be used to answer "what if ?" questions related to modifying patterns, explosives and blasting geometries. Such analysis can reduce or eliminate the need for costly field modifications of the above parameters. An estimate of the mean fragment size resultant from blasting can indicate the amount of energy, the type and size of equipment needed in subsequent comminution operations. An estimate of the size distribution can be used to evaluate the amount of fines and the proportion of large fragments which require secondary blasting or breakage and hinder materials handling operations. Where cost functions which relate production costs to the degree of fragmentation are derived, fragmentation estimation procedures can be used to determine optimum fragmentation which minimizes total production costs for a particular mining operation.

Several authors have attempted to devise procedures for empirical estimation of fragmentation. These procedures are determined by laboratory experiments, scaled field tests or actual production blasts. The main procedures found in recent published literature are described herein. No attempt is made to assess the accuracy of these procedures, other than general comments or sample results. Usually the authors of fragmentation estimation procedures are not overly concerned by the absolute accuracy of their procedures; relative accuracy to show changes occurring when blasting parameters are modified is often sufficient benefit from the application of a model. In addition, accurate predicting of the percentage of large fragments (boulders, oversize) is more important for most mining excavation and loading activities. The procedures examined are distinguished by the use of certain equations to predict the mean fragment size and

the use of other equations to describe the shape of the fragmentation size distribution curve.

The Kuz-Ram procedure was developed and popularized by Cunningham (1982, 1983, 1987). Integrated into industrial software packages, it has been used by several individuals in the mining industry. It is found to produce sufficiently accurate estimates of fragmentation to warrant its application as a decision tool in blast analysis investigations. The Kuz-Ram procedure has the advantages of having been used and (constructively) critiqued by several users, adaptable to various blasting parameters and geometries, and suitable for further development - as better knowledge is gained concerning the effects of rock properties and explosive-rock interactions.

The computer program described herein is a simple batch-type program for computing results from the Kuz-Ram procedure. Future program versions may include interactive input, graphic output and integration into complete blast evaluation systems. The examples illustrate the input data required and the effects of blasting parameters on both the mean fragment size and the complete size distribution. Sources of information are fully referenced.

2. THE KUZNETSOV EQUATION

Kuznetsov (1973) formulated a "*semi-empirical*" equation based on field investigations and review of previous published data which relates mean fragment size to mass of explosive, volume blasted and rock strength. The original form of the Kuznetsov equation is as follows:

$$\bar{x} = A\left(\frac{V_o}{Q}\right)^{4/5} Q^{1/6} \qquad [1]$$

where,

$\bar{x}$ = mean fragment size in cm.

A = Rock Factor (7 for medium rocks, 10 for hard and highly fissured rocks, 13 for very hard and weakly fissured rocks.)

Q = Mass of trinitrotoluene (TNT) in kilograms equivalent to the explosive charge in one blasthole.

V_o = Burden x Spacing x Bench Height (m^3).

Cunningham (1982) specifies:"*The concept of 'mean' fragment size requires explanation. In practical terms it is the mesh size through which half the rockpile will pass. Mathematically it is taken that all the fragments are cubes and that the fragment size is given by the cube root of the volume*". The Kuznetsov equation brings together in a logical and semi-empirical manner the fact that the resultant mean fragment size will be proportional to rock strength and volume blasted, and inversely proportional to the explosive charge per volume considered.

Cunningham (1983) shows how the basic equation is modified to treat other types of explosives relative to the performance of Ammonium Nitrate - Fuel Oil (ANFO) mixtures with the use of the following parameters in equation [2a]:

Q_e = Mass per blasthole of specific explosive being used and

E = Relative weight-strength of explosive (ANFO=100). (TNT is estimated to have a relative weight strength of 115).

$$Q_e \times E = Q \times 115 \qquad [2a]$$

Then:

$$Q = Q_e \times \frac{E}{115} \qquad [2b]$$

Substituting equation [2b] in [1]:

$$\bar{x} = A\left(\frac{V_o}{Q_e}\right)^{4/5} Q_e^{1/6} \left(\frac{E}{115}\right)^{1/6} \left(\frac{E}{115}\right)^{-4/5} \qquad [3a]$$

$$\bar{x} = A\left(\frac{V_o}{Q_e}\right)^{4/5} Q_e^{1/6} \left(\frac{E}{115}\right)^{-19/30} \qquad [3b]$$

Redefining Q as the mass of the specific explosive used ($=Q_e$) the modified Kuznetsov equation becomes:

$$\bar{x} = A\left(\frac{V_o}{Q}\right)^{4/5} Q^{1/6} \left(\frac{115}{E}\right)^{19/30} \qquad [4a]$$

where,

$\bar{x}$ = mean fragment size in cm.

A = Empirical rock factor

V_o = Volume per blasthole = Burden x spacing x bench height, in m^3

Q = Explosive mass per blasthole, kg above grade level, normally excluding explosive in subdrill section.

E = Relative weight strength of explosive (ANFO=100)

The modified equation can also be stated as a function of the powder factor, K. Defining K equal to Q/V_o in kilograms per m^3 the modified Kuznetsov equation can then be expressed as follows:

$$\bar{x} = AK^{-4/5} Q^{1/6} \left(\frac{115}{E}\right)^{19/30} \qquad [4b]$$

Cunningham (1987) further refined the estimation of the rock factor based on more detailed experiments and more precise actual assessments of fragmentation :

$$A = 0.06[RMD + JF + RDI + HF] \qquad [5]$$

where,

RMD = Rock Mass Description. Powdery, friable, RMD = 10. Vertically jointed, see JF. Massive, RMD = 50.

$$JF = JPS + JPA \qquad [6]$$

JPS = Vertical joint spacing. Less than 0.1, JPS = 10. From 0.1 to MS (defined oversize), JPS = 20. From MS to DP (drill pattern), JPS = 50.

JPA = Joint Plane Angle. Dip out of face, JPA = 20. Strike perpendicular to face, JPA = 30. Dip into face, JPA = 40.

RDI = Rock Density Influence RDI = 25RD - 50, RD = Density, tonnes per m^3, and

HF = Hardness Factor (Young's Modulus less than 50GPa, HF = Y/3; Young's Modulus greater than 50GPa, HF = UCS/5 where UCS is the uniaxial compressive strength in MPa).

This procedure for computing the value of A is significant in that it accounts for geomechanical rock mass properties in a more direct manner. Although the relationship between rock factor and mean fragment size remains linear, rock mass discontinuities and strengths measured in advance of blasting can be used for a preliminary estimate of factor A. Figure 1 illustrates the effect of the rock factor on mean fragmentation size. Figure 2 illustrates the effect of powder factor on mean fragmentation size. Values of A vary from 7 to 13, while values of K vary from 0.4 to 0.7 kg per m^3. The mass of ANFO ($E = 100$) is fixed at 50 kg ($= Q$).

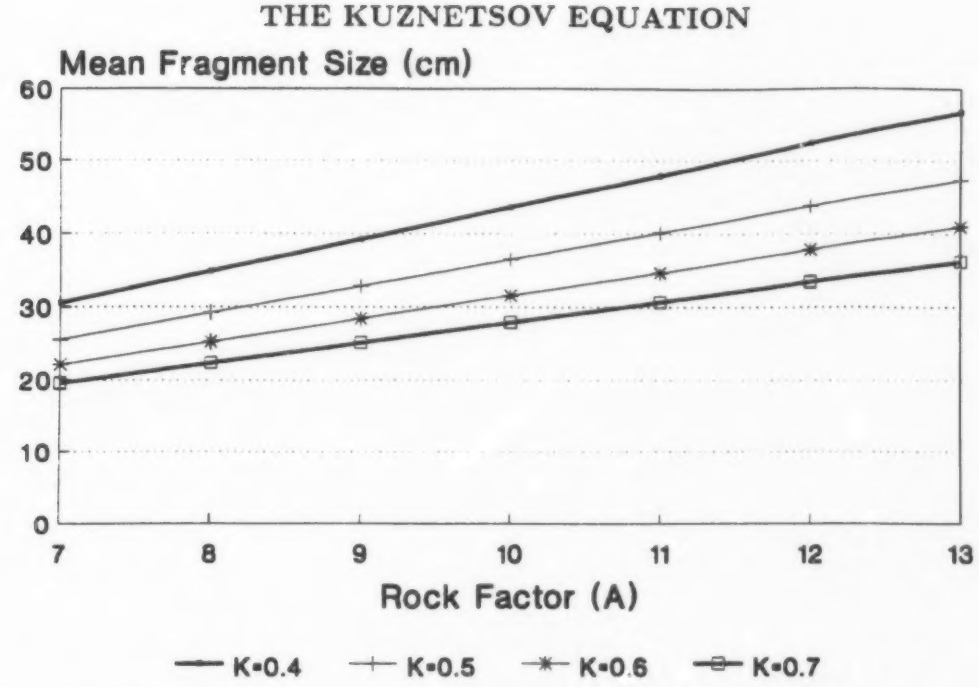

Figure 1. Effect of rock factor on mean fragment size (Kuznetsov)

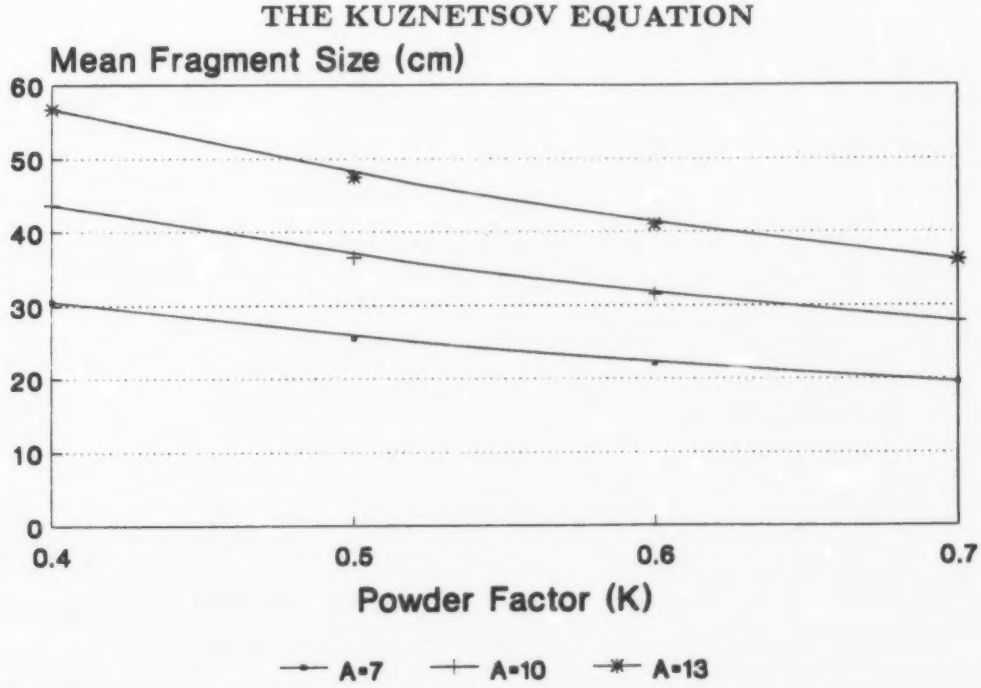

Figure 2. Effect of powder factor on mean fragment size (Kuznetsov)

3. THE ROSIN-RAMMLER EQUATION

3.1 The Rosin-Rammler Equation

The Rosin-Rammler equation is a well known equation used to characterize partical size distributions in a variety of applications; mineral processors are generally familiar with this equation which is described several authors such as Lovely (1973), Just (1979) and Cunningham (1982). It is algebraically expressed as follows:

$$R = e^{-\left(\frac{x}{x_c}\right)^n} \qquad [7]$$

where,

$R =$ mass fraction larger than size x.

$x =$ diameter of fragment, cm.

$x_c =$ characteristic size, cm.

$n =$ Rosin-Rammler exponent

$e =$ base of natural logarithms, 2.7183..

The characteristic size, x_c, is approximately the 36.8% size retainment point on the size distribution function. The Rosin-Rammler exponent, n, is known as the uniformity coefficient; a wide variety of size distributions can be modelled with the Rosin-Rammler equation by changing the value of n to fit the curve. Cunningham (1983) notes that the uniformity coefficient usually varies between 0.8 and 2.2. Figure 3 shows the different shapes the size distribution curves assume for this range of uniformity coefficient values. Cunningham (1987) further notes that for blasted rock, n is generally in the range 0.8 to 1.5 and is normally around 1.0. The uniformity coefficient controls the spread of the distribution; in most cases a higher value of n is preferred, signifying a more uniform distribution with less fines and oversize materials.

Since the mean size is obtained from the Kuznetsov equation, the characteristic size can be estimated once the value of 'n' is estimated with the following equations:

$$x_c = \frac{\bar{x}}{\sqrt[n]{-ln(0.5)}} \approx \frac{\bar{x}}{\sqrt[n]{0.6931472}} \qquad [8]$$

Although the Rosin-Rammler equation is well accepted in general, certain authors disagree with its ability to model distributions resulting from rock blasting. Lovely (1973)

notes that "*This equation tends to direct attention preferentially to the fine region, where it may represent the experimental data quite well. It does not give satisfactory fit to the full size range of data, however, and discrepancies in the coarse region may be large*".

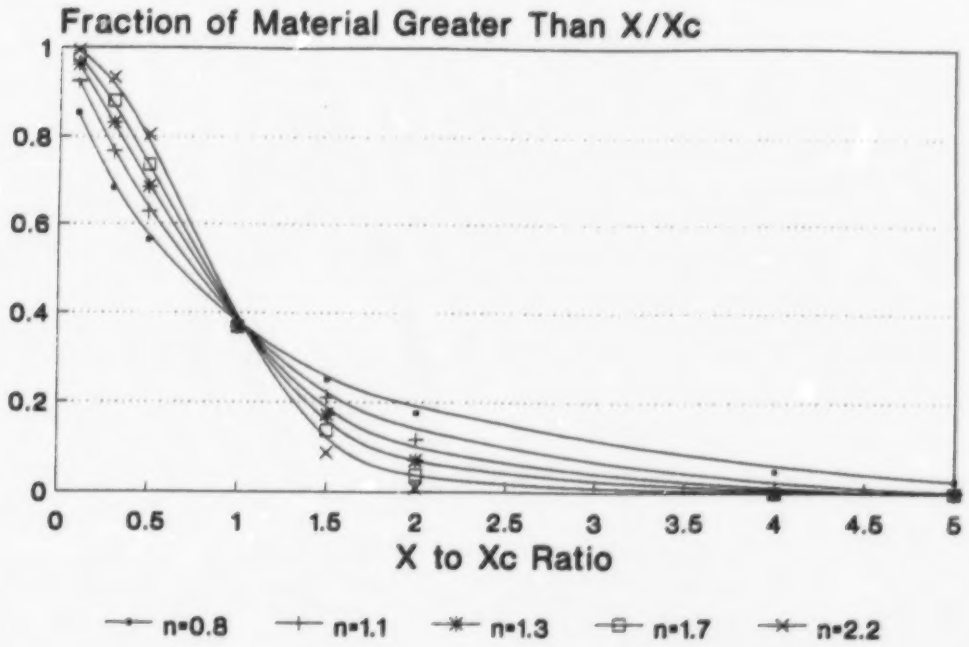

Figure 3. Effect of Rosin-Rammler coefficient on size distribution

3.2 Estimation of the Rosin-Rammler Parameters

A variety of procedures have been suggested to estimate Rosin-Rammler equation parameters to best fit experimental results in size distribution analysis. The Rosin-Rammler equation can also be expressed as follows:

$$lnln\left(\frac{1}{R}\right) = n(ln(x) - ln(x_c)) \qquad [9]$$

In this form, given that parameter n is considered constant for a specific blast, the size distribution plotted on log by log-log paper should appear approximately linear. The slope of the best-fit line will correspond to the uniformity coefficient n and the characteristic size x_c will correspond to the interpolated value of the 36.8% size retention on the line.

The Rosin-Rammler equation parameters can be assessed directly from the plot of the cumulative size distribution. Figure 4 shows three distributions as log versus log-log plots; characteristic size, x_c is 10 cm and uniformity coefficients are 1.0, 1.5 and 2.0 respectively.

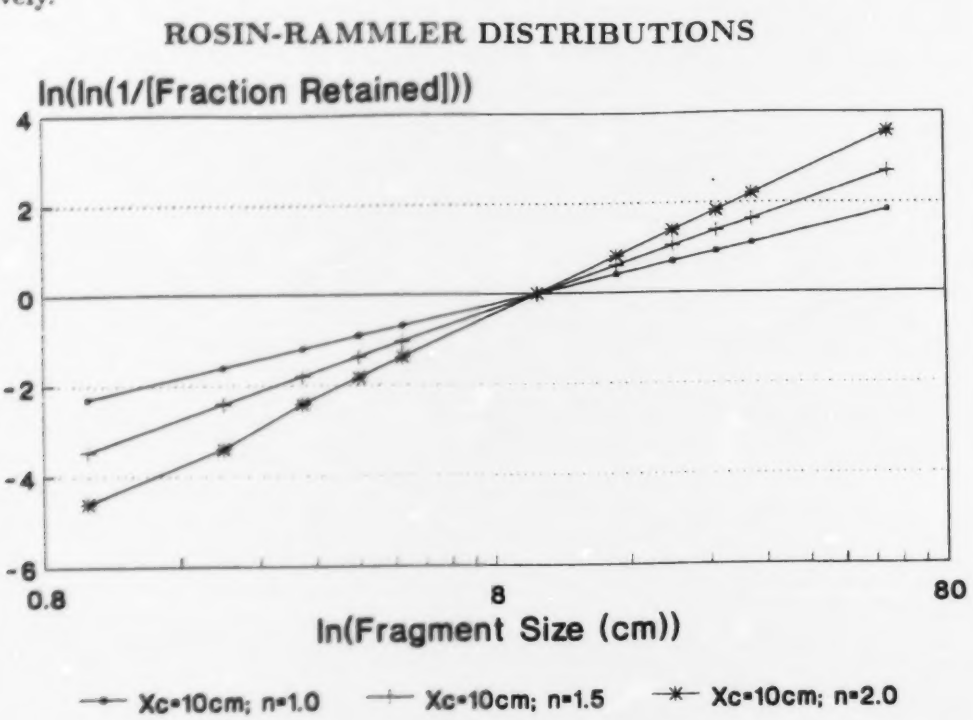

Figure 4. Illustration of Rosin-Rammler distributions

A variety of statistical methods are available to determine the distribution parameters. In addition, the Rosin-Rammler equation is identical to the Weibull distribution; this distribution is commonly used in reliability analysis to model various distributions of component and system failures. Harries (1979) notes the analogy between the distributions and Mutmansky (1970) describes the three parameter Weibull distribution, characterized by a density function:

$$f(x) = \frac{\alpha}{\beta}\left[\frac{x-\gamma}{\beta}\right]^{\alpha-1} e^{-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}} \qquad [10]$$

and a cumulative density function:

$$F(x) = 1 - e^{-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}} \qquad [11]$$

where,

α = Shape parameter ($\alpha > 0$)

β = Scale parameter

γ = Location parameter.

The Weibull distribution can assume a variety of shapes. For α equal to 1, the distribution is exponential; when α equals 1.5 the distribution is approximately log-normal; when α equals 3.6 the distribution is approximately normal. β extends or compresses the distribution. γ controls the position of the distribution along the abscissa; it represents the minimum value of the distribution. Mutmansky (1970) suggests various methods to determine the Weibull distribution parameters: the method of maximum likelyhood, the method of moments, the graphical method, and the method of least squares for transformed data.

Fragment size distributions resulting from blasting are not likely to have a minimum size, or at least the occurence of such a phenomenon cannot be directly physically explained. Thus the Weibull distribution can be reduced to two parameters with γ taking a value of zero. The cumulative Weibull function is then:

$$F(x) = 1 - e^{-(\frac{x}{\beta})^{\alpha}} \qquad [12]$$

In this form, it is evident that the shape parameter, α, is analogous to the uniformity coefficient (n) of the Rosin-Rammler equation [7] and the scale parameter, β, is analogous to the characteristic size, x_c, of the Rosin-Rammler equation.

3.3 The Rosin-Rammler Exponent

The most significant contribution of Cunningham (1982,1983,1987) was to relate the Rosin-Rammler exponent to blasting parameters. Given that the Kuznetsov equation accounts for explosive strength and rock mass characteristics, and that the mean size is related to the characteristic size of the Rosin-Rammler distribution, the only unkown left is the uniformity coefficient. Cunningham established the applicable uniformity coefficient through several investigations taking into consideration the impact of such factors as: blast **geometries**, hole diameter, burden, spacing, bottom and column charge lengths, hole length and drilling accuracy.

The exponent for the Rosin-Rammler equation is estimated as follows:

$$n = \left(2.2 - 14\frac{B}{d}\right)\left(\left[\frac{(1+S/B)}{2}\right]^{0.5}\right)\left(1 - \frac{W}{B}\right)\left[\frac{|BCL - CCL|}{L+0.1}\right]^{0.1}\left(\frac{L}{H}\right) \qquad [12]$$

where,

d = Hole diameter, mm.

B = Burden, m.

S = Spacing, m.

BCL = Bottom charge length, m.

CCL = Column charge length, m.

L = Total charge length, m.

W = Standard deviation of drilling accuracy, m.

W: Drilling accuracy is normally taken to have a standard deviation between 0.3m and 1.0m, depending on blasthole length, angle of drilling and local conditions.

H = Bench height, m.

Cunningham (1982) suggests n be increased by 10% for staggered patterns (compared to square patterns).

Limitations

Cunningham (1983) stipulates the following limitations with respect to the Kuz-Ram model:

a) The S/B ratio applies to the drilling, not the timing, layout and should not exceed 2.

b) Initiation and timing must be arranged so as to reasonably enhance fragmentation and avoid misfires or cut-offs.

c) The explosive should yield energy close to its calculated Relative Weight Strength.

d) The jointing and homogeneity of the ground require carefull assessment, as fragmentation is often built into the rock structure especially when loose jointing is more closely spaced than the drilling pattern.

The modified Kuznetsov equation [4a], the Rosin-Rammler equation [7] and the estimate of the Rosin-Rammler exponent form the basis of the **Kuz-Ram procedure** for blast fragmentation estimation developed by C.V.B. Cunningham.

4. OTHER FRAGMENTATION ESTIMATION EQUATIONS

A number of different fragmentation estimation procedures, for predicting mean fragment size, and fragmentation distribution equations are reviewed herein. The objective is to present the procedures most frequently referred to, in order to compare the general form of the equations to the equations used in the Kuz-Ram procedure. Full comparison would necessitate field tests and more detail on certain of the procedures than is presently available from publications.

4.1 Swedish Detonic Research Foundation (SveDeFo)

The Swedish Detonic Research Foundation developed a procedure for estimating the mean fragment size based on explosive energy, rock mass strength and blasting parameters. The procedure is summarized in slightly different form in equations by Hjelmberg (1983) and Rustan (1987):

A. SveDeFo Equation (Hjelmberg (1983))

$$k_{50} = Sf\left(\frac{h}{H}\right)e^{\left[0.29ln\left(V^2\sqrt{\frac{E}{V}}\right) - 1.18ln\frac{q}{c} - 0.82\right]} \qquad [13a]$$

where,

k_{50} = Fragmentation factor, the side (m) of a quadratic screen through which 50% of the loosened rock may pass.

S = Blasting factor

$f\left(\frac{h}{H}\right)$ = Function relating uncharged part (h) to hole length (H).

V = Burden, m.

E = Spacing, m.

q = Specific charge (kg DxB/m^3)

c = Rock constant (kg DxB/m^3)

B. SveDeFo Equation (Rustan (1987))

$$k_{50} = s\left[1 + 4.67\left(\frac{h_0}{H}\right)^{2.5}\right]e^{0.29lnB^2\sqrt{\frac{S}{1.25}} - 1.18ln(\frac{q}{c}) - 0.82} \qquad [13b]$$

where,

k_{50} = The mesh size where 50 weight - % of the material passes.

q = Specific charge, (kg/m^3)

s = Structure factor: 0.60, highly fractured rock; 0.55, fractured rock; 0.50, lightly fractured rock; 0 45, almost homogeneous rock; 0.40, homogeneous rock.

h_0 = Uncharged part of blasthole, m.

H = Depth of blasthole, m.

B = Burden, m.

S = Hole distance, m.

c = Rock constant according to Langefors definition. Amount of Dynamex M (kg/m^3)

4.2 The Da Gama Equations

Da Gama (1983) developed techniques for applying the fundamental comminution equations enounced by F.C. Bond (for crushing and grinding) to rock fragmentation by explosives blasting. The work of F.C. Bond consisted in formulating a procedure for estimating the energy required to fragment material from any given mean size to a reduced mean size. This procedure relies on laboratory determination of the 'Bond Work Index', well known to mineral processors. Da Gama (1983) cautions that *"Reliability of this analysis depends on the accurate determination of a valid work index for the rock mass, which must be obtained earlier by appropriate field tests"*. The fundamental Bond equation relates energy input to fragmentation achieved (in kWh per ton of processed material) and can be expressed in the following form:

$$W = 10W_i\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \qquad [14]$$

Where:

W = Energy required for fragmentation, kWh per ton of material.

P_{80} = Product 80% passing, microns.

F_{80} = Feed 80% passing, microns.

W_i = Bond's work index, which may be defined as the energy required to crush a solid of infinite size to a product which size 80% passing is 100 microns.

For a bench blast, assuming the bench is made up of intact rock, its F_{80} is practically infinite, the Bond equation becomes:

$$W = \frac{10W_i}{\sqrt{P_{80}}} \qquad [15]$$

where,

W = is the energy released in the blast, kWh per ton of broken rock, and calculated from the heat content of the explosive.

Da Gama (1983) proposed the estimation of the size distribution of fragments with the following empirical formula:

$$P_S = aW^b\left(\frac{S}{B}\right)^c \qquad [16]$$

where,

P_S = % cumulative undersize weight of the fraction size S.

W = total explosive energy input per unit weight of blasted rock, kWh per ton.

B = Burden of the charges, m.

a, b, c = empirical factors dependent on the explosive type, rock properties and blasting pattern.

Da Gama notes that: *"Use of these expressions requires the previous determination of constants a, b and c from a series of field tests, conducted under the same conditions as the prediction of fragmentation will be done - no extrapolation is valid in order to quantify cases of blasting in jointed rock masses."* Fragmentation in this case will be controlled by structural discontinuities. Da Gama suggests a modified formula for fragmentation estimation in jointed rock masses:

$$P_S = aW^b\left(\frac{S}{B}\right)^c \frac{1}{{F_{50}}^d} \qquad [17]$$

The addition of one more factor seems to properly quantify the 'feed distribution' (*in situ* size distribution created by joint planes). *"The values of a, b, c, and d must be obtained in previous blasts designed to measure fragmentation in a range of different situations where prescribed variations of W and B are imposed."* Borquez (1986) illustrates how

parameters of the Da Gama equation can be estimated from measured fragmentation and an estimate of the Bond Work Index parameter for a specific rock type.

4.3 The Gaudin-Meloy Equation

Lovely (1973) and Just (1979) describe the Gaudin-Meloy equation for characterizing fragment size distributions:

$$R = 1 - \left[1 - \frac{x}{x_0}\right]^r \qquad [18]$$

where,

R = Cumulative proportion of material retained on a screen opening of size 'x'.

x = Particle or aperture size.

x_0 = Largest particle size in the distribution, determined mathematically from the equation representing the best fit to the data (Just (1979)). Also particle size prior to fracture (Lovely (1973)).

r = Gaudin-Meloy exponent

Lovely (1973) notes: "*The Gaudin-Meloy equation is particularly suited to describing the coarse region of sizings, but generally fails in adequately representing the fines. When plotted, the fines are contracted, and the coarse end expanded with a finite upper limit*".

4.4 The Schuhmann Equation

Just (1979) describes the Schuhmann equation for characterizing size distributions as follows:

$$R = 1 - \left[1 - \frac{x}{x_0}\right]^m \qquad [19]$$

where,

R = Cumulative proportion of material retained on a screen opening of size 'x'.

x = Particle or aperture size.

m = Schuhmann distribution modulus. Slope at fine end of the distribution.

x_0 = The theoretical (constant) intercept of the straight-line portion of the curve at 100% passing.

4.5 The Just Equation

Just (1973, 1979) presents empirical equations for the estimation of blast fragmentation distributions. A particularity in this case is the implicit consideration of the optimum depth of burial of the explosive charge.

The cumulative percent passing is estimated using the following equation:

$$Y = e^{4.8\left(\frac{x}{D}\right)^g} \qquad [20]$$

where,

Y = cumulative percent passing screen size x

D = optimum depth for the weight of explosive detonated (charge depth which produces the maximum crater volume)

g = fragmentation gradient

The fragmentation gradient can be estimated by using the following equation:

$$g = \frac{R^2}{F} = \frac{1}{F} \times \left(\frac{d}{D}\right)^2 \qquad [21]$$

where,

g = fragmentation gradient

D = optimum depth

d = actual charge depth

R = charge depth ratio

F = fragmentation factor.

Just (1973, 1979) remarks " *The fragmentation factor was found to be constant for a given explosive type, rock type and explosive distribution*".

4.6 Other Equations

Several other authors have attempted to predict fragmentation by the use of empirical relationships. They are characterized by individually allowing for consideration of a limited number of essential parameters and have not found general use. Slotky et al (1985) describe a Mott distribution function for characterizing fragmentation which models the linear size of fragments. A particularity of the model is the consideration of fragment size as a function of the distance from the explosive charge. The effects of explosive properties, rock type, delays, specific charge, geometric scale, rock mass physical properties and discontinuities, burden, etc., have been studied by several authors, including Bergmann (1983), Rustan et al (1983), Rustan and Nie Shu Lin (1987). Other information can also be obtained by examining the proceedings of the First and Second '*International Symposium on Rock Fragmentation*' which appear in the references.

5. PARAMETRIC ANALYSIS: KUZ-RAM PROCEDURE

The Kuz-Ram procedure is based on the application of the modified Kuznetsov equation [4a], the Rosin-Rammler equation [7] and the estimate of the Rosin-Rammler exponent [12]:

$$\bar{x} = A\left(\frac{V_o}{Q}\right)^{4/5} Q^{1/6}\left(\frac{115}{E}\right)^{19/30} \qquad [4a]$$

where,

$\bar{x}$ = mean fragment size in cm. A = Empirical rock factor. V_o = Volume per blasthole = Burden x spacing x bench height, in m^3. Q = Explosive mass per blasthole, kg above grade level. E = Relative weight strength of explosive (ANFO = 100)

$$R = e^{-\left(\frac{x}{x_c}\right)^n} \qquad [7]$$

where,

R = mass fraction larger than size x. x = diameter of fragment, cm. x_c = characteristic size, cm. n = Rosin-Rammler exponent. e = base of natural logarithms, 2.7183..

$$n = \left(2.2 - 14\frac{B}{d}\right)\left(\left[\frac{(1+S/B)}{2}\right]^{0.5}\right)\left(1 - \frac{W}{B}\right)\left[\frac{|BCL - CCL|}{L + 0.1}\right]^{0.1}\left(\frac{L}{H}\right) \qquad [12]$$

where,

d = Hole diameter, mm. B = Burden, m. S = Spacing, m. BCL = Bottom charge length, m. CCL = Column charge length, m. L = Total charge length, m. W = Standard deviation of drilling accuracy, m. H = Bench height, m.

A computer program, written in FORTRAN, is available to compute the mean size, the Rosin-Rammler exponent and the fragmentation size distribution with the Kuz-Ram model. The program is listed and described in Appendix A. Preliminary calculations are required to estimate drilling and blasting parameters and the rock factor (A) of equation [4a].

The following two short case studies illustrate how the Kuz-Ram procedure can be applied to analyze the effects of various drilling, blasting and geomechanical rockmass properties on predicted fragmentation. The examples are appropriate for showing how

the Kuz-Ram model could be calibrated to permit estimation of the *relative changes* in fragmentation accompanying changes in surface and underground blast pattern designs.

5.1 Open-pit Blast Fragmentation Simulation

The first case study example illustrates application of the Kuz-Ram procedure for blast pattern design in an open-pit mining operation. The example is partially based on the study reported by Borquez (1986) in which a stochastic simulation was performed to assist in the selection of the optimum blast pattern. Borquez specifies that the criterion for pattern selection is based on the minimization of total mining costs. The study also considered the setting of a jaw crusher and the maximum size it could handle in order to assess the amount of secondary blasting which is necessary. Borquez (1986) notes: "*The desired fragmentation for the daily capacity of the operation should be such that secondary blasting will not be required for more than 5% of the total ore blasted. The constraint is imposed on the secondary blasting because this method of size reduction is very expensive. In many instances this item comprises about 30% of the total drilling and blasting costs*". The simulation model for crusher sizing thus included estimates of all costs as a function of fragmentation; the total cost curve produced is characteristically (as expected) U shaped, indicating a burden at which costs are minimized. The case presented here only examines the fragmentation prediction, with similar ranges of parameters examined by Borquez (1986).

A relatively hard iron ore with a specific gravity of 5.0 is considered. A range of possible burdens between 4.5 and 6.4 meters is analysed. The initial case called for a 9.5m by 9.5m drill pattern for blasting at an echelon of 45°, producing a 6.4m burden; to simplify, this is considered equivalent to a 6.4m by 14.1m square pattern for the purpose of applying the Kuz-Ram model (although slightly above the recommended maximum S to B ratio range). The rock factor (A) is selected to vary between 9.5 and 10.5, based on the average compressive strength of 28000psi (approximately 193MPa). Blast parameters and input data for the Kuz-Ram program are shown in Table 1. The results of the case study are fully listed in Appendix B and summarized in Table 2. The weight percentage of material retained for 25cm and 130cm are noted, since they correspond to the crusher setting and the maximum size it can handle, respectively.

The first observation to be made in examining the results presented in Table 2 is the considerable difference in estimated mean sizes compared to the results obtained by Borquez (1986). The Kuz-Ram model produced mean sizes, on an average, 2.5 times the values predicted by the Da Gama equation. The difference can partly be explained by considering the two main factors which influence the mean size in the Kuznetsov equation. The rock factor is estimated by considering the iron ore as quite hard with

a high compressive strength; no information is provided for evaluating the amount of jointing or other rock characteristics. The second factor is the explosive energy per unit of volume; the pattern being fixed this parameter can only be modified by using a higher weight strength explosive. Borquez indicates that slurries are also used but does not specify their proportions relative to the ANFO used. Insufficent details are available to compare the two models. Large differences also occur in the amount of '*spread*' in the distributions; the Rosin-Rammler exponent is estimated (graphically) to be about 0.65 for distributions shown by Borquez, while values of about 1.80 were computed with the Kuz-Ram model.

Table 1. Summary of information: open-pit simulation

Diameter of blasthole: 318.mm	Bench height: 13m
Charge length: 10.5 m	Burden: 4.5m, 5.6m, 6.7m
Spacing: 10.0m 12.3m, 14.1m	Explosive per hole: 709. kg
Rock factor: 9.5, 10.0, 10.5	S.G. of explosive: 0.85
S.G. of rock: 5.0	Drilling accuracy: 0.5m
Rectangular drilling pattern	Volume per blasthole: 585,
Explosive: ANFO (E=100)	895 and 1173 cubic meters

Table 2. Summary of results: open-pit simulation

Rock Factor	9.5	10.0	10.5
Mean Fragment Size, cm.			
Burden = 4.5m	26.58	27.98	29.38
Burden = 5.6m	37.36	39.33	41.30
Burden = 6.4m	46.38	48.82	51.26
Percentage Weight Greater Than 130 cm (%)			
Burden = 4.5m	0.00	0.00	0.00
Burden = 5.6m	0.10	0.20	0.30
Burden = 6.4m	1.10	1.60	2.30
Percentage Weight Greater Than 25 cm (%)			
Burden = 4.5m	53.8	56.9	59.7
Burden = 5.4m	71.7	73.9	75.8
Burden = 6.4m	79.8	81.4	82.9

Figures 5, 6 and 7 illustrate the full size distributions obtained for rock factors of 9.5, 10.0 and 10.5 respectively. Figure 8 shows the effect of burden selection on mean size and the percentage retained at a grid size of 25 cm. The percentage at 25cm and 130cm (Table 2) were computed from the Rosin-Rammler parameters determined with the Kuz-Ram computer program.

The information produced with the Kuz-Ram model and illustrated in the preceding graphs can be used in a variety of ways to optimize the drilling and blasting patterns for an open-pit operation. Fragmentation predictions can be integrated into a stochastic simulation model in which values can be '*pulled*' from the preceding graphs as a function of the drill pattern being analyzed. The procedure produces estimates of full size distributions, which may be useful in predicting the amount of energy required for comminution and forecasting the crusher throughput.

Although the case study is only presented for the purpose of illustrating the general Kuz-Ram procedure, the wide discrepancies with results presented by Borquez (1986) indicate that caution must be taken in applying the model without specific data from the operation through field trials.

The case study can also be used to show the range of results that can be expected when blast patterns are designed for average conditions. Some indication is provided of the potential savings which could be gained by tailoring each blast as a function of measured rockmass properties. Although the range of rock factors, A, simulated is quite small, significant changes in predicted oversize are indicated.

The focus of the case study, as the study presented by Borquez (1986), is on estimating oversize, defined as the size requiring secondary blasting because of the selected crusher maximum opening (130 cm). For example blocks of 100 cm, while they may be loaded and hauled may hinder operations by increasing shovel load time and increase loading and haulage equipment maintenance. The Kuz-Ram conveniently provides the entire distribution for such possible future studies.

KUZ-RAM MODEL: ROCK FACTOR = 9.5

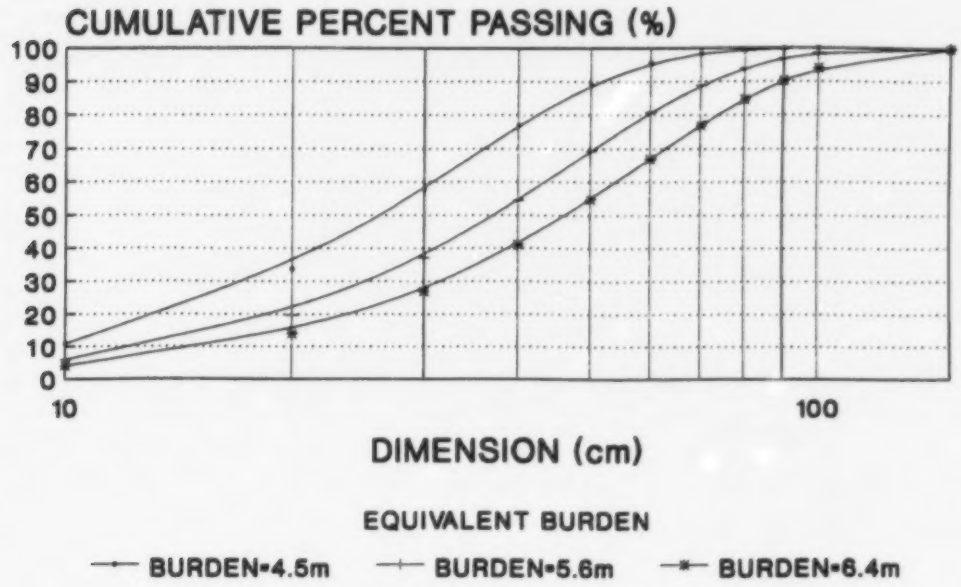

Figure 5. Open-pit simulation, rock factor = 9.5

KUZ-RAM MODEL: ROCK FACTOR = 10.0

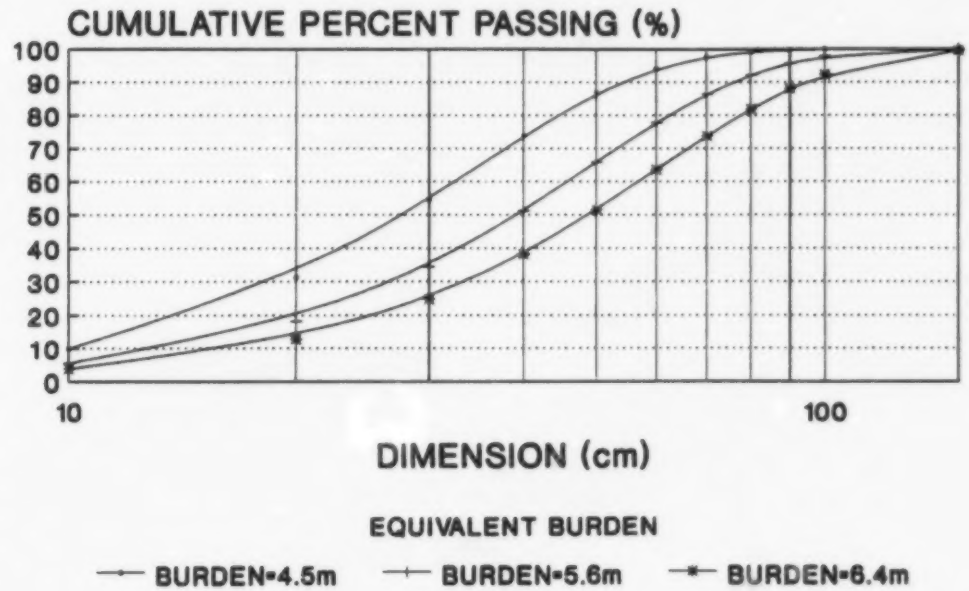

Figure 6. Open-pit simulation, rock factor = 10.0

KUZ-RAM MODEL: ROCK FACTOR = 10.5

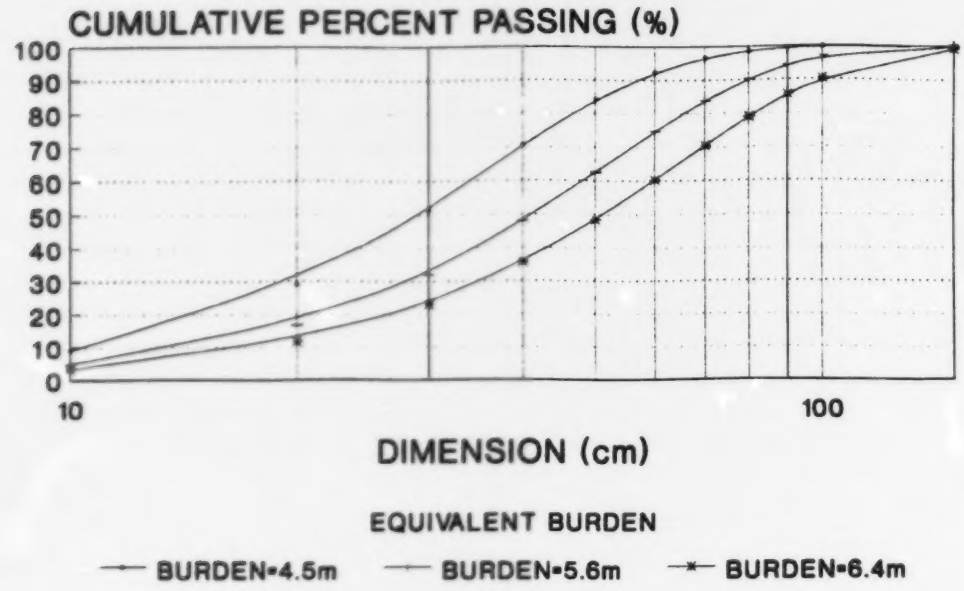

Figure 7. Open-pit simulation, rock factor = 10.5

KUZ-RAM MODEL: MEAN SIZE AND % GREATER THAN 25cm

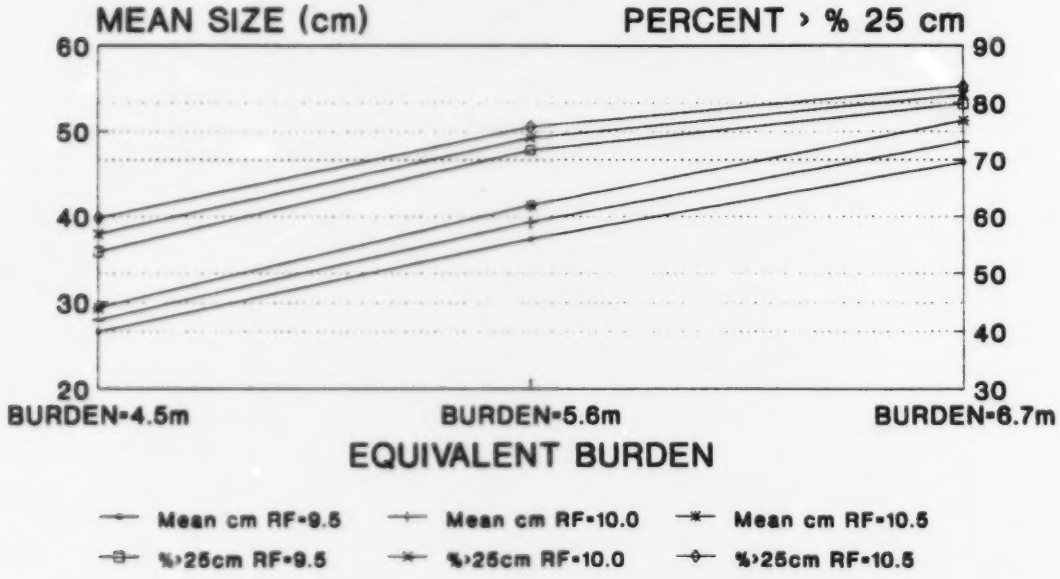

Figure 8. Open-pit simulation, mean size and % greater than 25cm

5.2 Blasthole Stoping Blast Fragmentation Simulation

This case study example demonstrates the usefulness of the Kuz-Ram procedure for blast fragmentation analysis in the case of underground mining with blasthole stoping. The case considers blasthole stoping with 127mm diameter holes and a stope height (bench height) of 30.0m in a massive sulphide deposit. A portion of the input parameters are adapted from Chitombo *et al* (1987).

The parameters for the blasthole stoping simulations are provided in Table 3. The case study example is used to demontrate the effect of drillhole deviation on oversize produced. In this case oversize is considered material above 100cm. The drilling pattern is 3.5m by 4.0 with full length charges. Rock strengths are varied from 8 to 10 and drilling accuracy is varied from 0.0m to 1.0m, variations suggested by Cunningham (1983). Results are reported for these nine basic cases with other simulations executed to assess intermediate values.

Table 3. Summary of information: blasthole stoping simulation

Diameter of blasthole: 127.mm	Bench height: 30m
Charge length: 30.0 m	Burden: 3.5m
Spacing: 4.0m	Explosive per hole: 304. kg
Rock factor: 8, 9 and 10	S.G. of explosive: 0.8
S.G. of rock: 4.0	Drilling accuracy: 0., .5, 1.
Rectangular drilling pattern	Volume per blasthole: 420c.m.
Explosive: ANFO (E=100)	

The Kuz-Ram model is applied to underground blasthole stoping with parallel drillholes because it is similar to surface bench blasting. It should be noted, however, that the model was not initially intended for this purpose. Blasthole stoping is different since the 'bench' is fully undercut which eliminates 'toe' type problems; no stemming is used in this case; in other situations decking of charges may be required for such long holes. Preliminary tests have shown that the results are sufficiently accurate for simple blast geometries to continue using the Kuz-Ram for initial estimate purposes in underground mining.

The results of nine program executions are summarized in Table 4 and fully reported in Appendix C.

Table 4. Summary of results: blasthole stoping simulation

Rock Factor	8	9	10
Mean, cm.	29.35	33.02	36.69
n W=0.0	1.90	1.90	1.90
n W=0.5	1.62	1.62	1.62
n W=1.0	1.35	1.35	1.35
Percentage greater than 100cm			
W=0.0	0.08	0.35	0.97
W=0.5	0.62	1.51	2.91
W=1.0	2.61	4.47	6.76
90% cumulative passing size, cm.			
W=0.0	55.3	62.2	69.11
W=0.5	61.4	69.1	76.8
W=1.0	71.2	80.1	89.0

Figure 9 illustrates characteristic size distributions determined for a drilling accuracy of 0.5m for the rock factors tested. Figure 10 shows the significant differences in oversize material as drilling accuracy is modified from 0.0m to 1.0m. Cunningham suggest that this is a plausible range for drilling accuracy. In an underground environment with relatively long drillholes, larger deviations may be common. In addition to hindering loading and producing material for secondary blasting, large blast muck can also induce blockage (arching) of drawpoints and ore passes; oversize material also requires more handling and causes more delays than in surface operations.

CHARACTERISTIC SIZE DISTRIBUTIONS

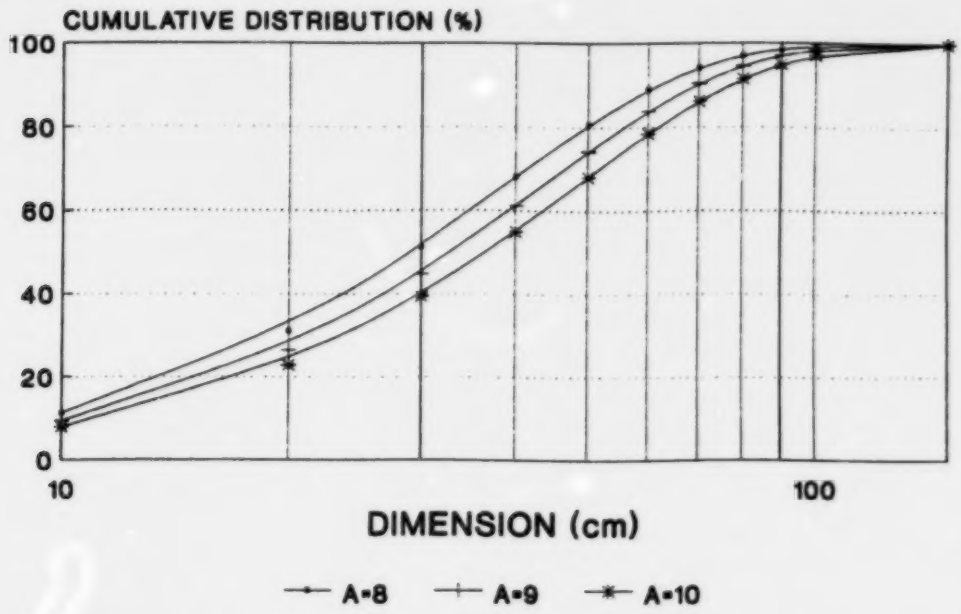

Figure 9. Blasthole stoping: characteristic size distributions

MEAN FRAGMENT SIZE AND PERCENTAGE OVERSIZE

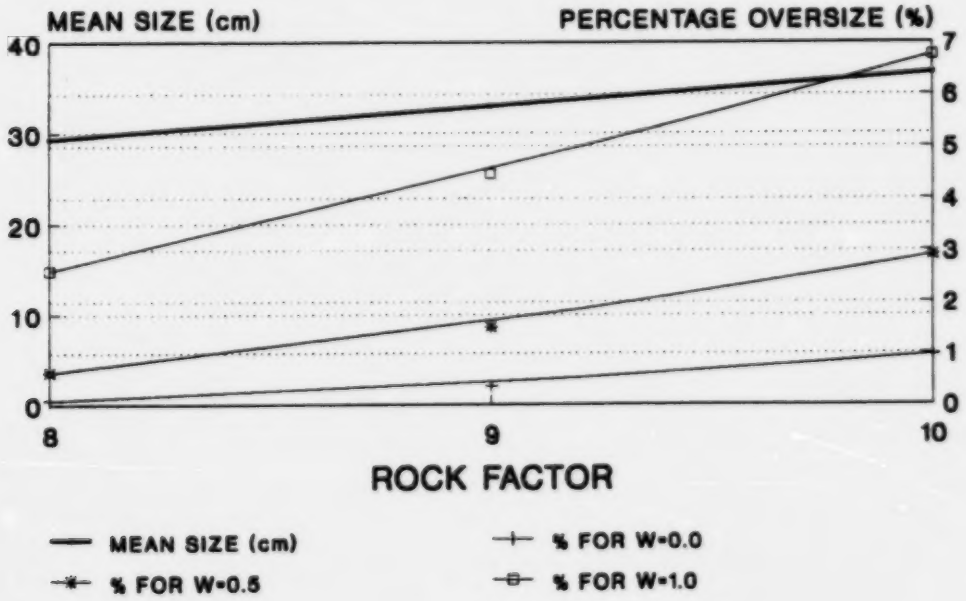

Figure 10. Blasthole stoping: mean fragment size and percentage oversize

6. DISCUSSION

The empirical procedures described in this text are not fully evaluated and their validity, accuracy and precision have not been measured. Although the shape of the size distribution curves can be illustrated, full evaluation and comparison necessitates field tests under controlled conditions. Each model would need to be calibrated according to local field test conditions.

The Kuz-Ram has the distinct advantage of being applicable with very little field data available. In this case it can be used to assess *relative change*. However, the case study demonstrates that caution must be taken in extrapolating conclusions from such theoretical studies. Because of the numerous users of the Kuz-Ram model it will undoubtably improve to permit its use for such preliminary analysis applications in the near future. The model has definite weaknesses regarding consideration of explosives distribution, blast timing and rockmass characterization; conversely it remains simple and easy to apply as a first estimate. Although a new empirical model can apparently be devised for each test blast, it is recommended to initially try to adjust the Kuz-Ram model.

7. CONCLUSIONS

Several empirical prediction formulas have been established for estimating rock fragmentation by explosives blasting. These formulas take into consideration rockmass characteristics, explosives strengths and blast geometry to various extents. The Kuz-Ram procedure is apparently the most comprehensive procedure and can be useful for preliminary estimates of fragmentation and for integrated studies of fragmentation effects on productivity and total production costs. The procedures described herein nevertheless remain **empirical estimation methods** which should be supported by field calibration, to establish acceptable accuracy when used for the purpose of modifying blast design.

REFERENCES

1. Bergmann, O.R., *Effect of explosive properties, rock type and delays on fragmentation in large model blasts*, First International Symposium on Rock Fragmentation by Blasting, Luleå, Sweden, August 1983, 71-78.

2. Borquez, G.V., *Use of a risk analysis model to evaluate rock fragmentation by blasting and to determine the size of a primary crusher*, Society of Mining Engineers of AIME, Fall Meeting, St-Louis, Missouri, September 1986, Preprint 86-311.

3. Chitombo, G.D., Crowther, G.C., Flewelling, S.B., *Brunswick Mining 49-8 primary stope study*, CIM Annual General Meeting, Toronto, May 1987, Paper 161a.

4. Cunningham, C.V.B., *Rock fragmentation related to blast design*, The Institute of Quarrying of South Africa, March 1982, 11 p.

5. Cunningham, C.V.B., *The Kuz-Ram model for prediction of fragmentation from blasting*, First International Symposium on Rock Fragmentation, Luleå, Sweden, August 1983, 439-454.

6. Cunningham, C.V.B., *Fragmentation estimations and the Kuz-Ram model - Four years on*, Second International Symposium on Rock Fragmentation, Keystone, Colorado, August 1987, 475-487.

7. Da Gama, C.D., *Use of comminution theory to predict fragmentation of jointed rock masses subjected to blasting*, First International Symposium on Rock Fragmentation by Blasting, Luleå, Sweden, August 1983, 565-579.

8. Harries, G., Blasting as a comminution process, Fourth Tewksbury Symposium, Melbourne, February 1979, 23.1-23.7.

9. Hjelmberg, H., *Some ideas on how to improve calculations of the fragment size distribution in bench blasting*, First International Symposium on Rock Fragmentation by Blasting, Luleå, Sweden, 1983, 469-494.

10. Just, G.D., *The application of size distribution equations to rock breakage by explosives*, National Symposium on Rock Fragmentation, Australian Geomechanics Society, Adelaide, February 1973, 18-23.

11. Just, G.D., *Rock fragmentation in blasting*, CIM Bulletin, March 1979, 143-148.

12. Kuznetsov, V.M., *The mean diameter of the fragments formed by blasting rock*, Soviet Mining Science, Vol 9-3, 1973, 39-43.

13. Lovely, B.G., *A study of the sizing analysis of rock particles fragmented by a small explosive blast*, National Symposium on Rock Fragmentation, Australian Geomechanics Society, Adelaide, February 1973, 24-34.

14. Mutmansky, J.M., A distribution-fitting method for general use, Decision-Making in the Mineral Industry, CIM Special Volume 12, Montreal, 1970, 486-491.

15. Rustan, A, Vutukuri, V.S., Naarttijärvi, T., *The influence from specific charge, geometric scale and physical properties of homogeneous rock on fragmentation*, First International Symposium on Rock Fragmentation by Blasting, Luleå, Sweden, August 1983, 115-142.

16. Rustan, A., Nie Shu Lin, *New methods to test the rock breaking properties of explosives in full scale*, Second International Symposium on Rock Fragmentation by Blasting, Keystone, Colorado, August 1987, 36-47.

17. Slotky, D., Jaeger, Z., Englman, R., *Distribution of fragments in a series of explosions in the Rotem Oil Shale Fields - Theory and Experiments*, First Mini-Symposium on Explosives and Blasting Research, Society of Explosives Engineers, San Diego, California, January 1985, 130-140.

APPENDIX A

THE KUZ-RAM COMPUTER PROGRAM

This appendix contains the listing of the FORTRAN program for computing fragmentation distributions based on the Kuz-Ram procedure. Instructions are supplied for creating a data file and executing the program. A sample output listing illustrates the current format output.

INPUT PARAMETERS FOR KUZ-RAM COMPUTER PROGRAM

A data file is created and contains required information, in free format, line by line as described below.

KUZ-RAM INPUT DATA FILE

LINE	VARIABLES	DESCRIPTIONS
1	TITLE	Title of program execution for output. Maximum of 70 alpha-numeric characters
2	DIAMET	Diameter of blastholes, mm.
3	HEIGHT, CHARGL, BURDEN,SPACIN	Bench height, m, Charge length, m, Burden, m, Spacing, m.
4	ROCKFA, SPECIF, RWEIST,DACCSD	Relative rock factor, Specific gravity of explosive, Relative weight strength of explosive, ANFO=100, Standard deviation of drilling accuracy, m.
5	NSTAGG, BCL, CCL, SPROK	Drilling layout, 0 for rectangular, 1 for staggered (increases the computed value of 'n' by 10%), Bottom charge length, m, Column charge length, m, Specific gravity of rock.

PROGRAM OUTPUT

- Predicted mean fragment size, cm. Rosin-Rammler characteristic size, (x_c), cm. Exponent for size distribution curve shape, (n).
- Approximate powder factor, kg of explosive per ton of rock.
- Percent retained and cumulative percent passing from sixteenth to sixteen times the predicted mean fragment size.
- Fragment sizes for percent retained and percent cumulative passing for fixed 10 percent increments.
- Percent retained and percent cumulative passing for 1, 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150 and 200 cm.

The output can be easily modified to provide various elements of the size distribution to suit particular needs. The above values are thought to be the essential values necessary for fragmentation size distribution analysis. Modifications can be made by changing the data statements at the start of the program and recompiling.

The compiled program is executed with the input data file specified and the location for the output. The listing shown is written for a VAX in which default devices for READ and WRITE statements are: 4 corresponds to the input data file, 6 is the screen and 8 is the default output file (FOR008.DAT) for the VAX. The code lines which refer to these devices would need to be changed for use on another computer.

An input data file example is listed below. The results obtained with this data file are shown after the computer program listing.

INPUT DATA FILE EXAMPLE

```
Line 1:     SAMPLE INPUT DATA FILE
Line 2:     165.
Line 3:     14.0    14.0    3.0     3.0
Line 4:     10.0    0.80    100.    0.3
Line 5:      0      0.0     14.0    2.8
```

COMPUTER PROGRAM LISTING
FRAGMENTATION PREDICTION: KUZ-RAM MODEL

```
0001    C     ++++++++++++++++++++++++++++++++++++++++++++++++++++++++
0002    C          FRAGMENTATION PREDICTION - KUZ-RAM MODEL
0003    C          ----------------------------------------
0004    C     This program is based on the procedure presented by
0005    C     C.V.B. Cunningham using the modified Kuznetsov equation
0006    C     with the Rosin-Rammler equation. The objective is to
0007    C     attempt to predict the size distribution of fragmentation
0008    C     resulting from blasting. References: Cunningham, 82-83-87
0009    C
0010    C     Y.C. Lizotte  1989/06
0011    C
0012    C     DEFINITION OF INPUT VARIABLES
0013    C     -----------------------------
0014    C                                                  VARIABLE
0015    C                                                  --------
0016    C     Title: Title of simulated fragmentation        TITLE
0017    C     d:     Hole diameter - mm                      DIAMET
0018    C     H:     Bench height  - m                       HEIGHT
0019    C     L:     Charge length above grade - m           CHARGL
0020    C     BCL:   Bottom charge length - m                BCL
0021    C     CCL:   Column charge length - m                CCL
0022    C     B:     Burden - m                              BURDEN
0023    C     S:     Spacing -  m                            SPACIN
0024    C     A:     Rock factor - relative                  ROCKFA
0025    C     sg:    Specific gravity of explosive           SPECIG
0026    C     E:     Relative weight strength explosive      RWEIST
0027    C            (ANFO=100)
0028    C     W:     Standard deviation - drill
0029    C            accuracy - m                            DACCSD
0030    C     DL:    Drilling layout (0 = rectangular,
0031    C            1 = staggered- increase n by 10%)       NSTAGG
0032    C     SPROK: Specific gravity of rock                SPROK
0033    C
0034    C     MAIN COMPUTATIONS
0035    C     -----------------
```

```
0036    C                                                    VARIABLE
0037    C                                                    --------
0038    C       Rsb:    Ratio of spacing to burden             RSB
0039    C       Q:      Explosive mass per hole, kg            XMASS
0040    C       Vo:     Volume per blasthole - m^3             VOLPBH
0041    C       n:      Shape of curve - Rosin-Rammler         XNRR
0042    C       x:      Mean size - Kuznetsov - cm             XBARK
0043    C       xc:     Characteristic size - cm               XCRR
0044    C       R:      Fraction passing for size x            FRACRR
0045    C       Powf:   Approximate powder factor - kg/t       POWF
0046    C
0047    C       PROGRAM OUTPUT: Size distribution of fragmented rock
0048    C                       as a function of input parameters.
0049    C                       Values are computed from sixteen times
0050    C                       smaller to sixteen times larger than mean
0051    C       ++++++++++++++++++++++++++++++++++++++++++++++++++++++++
0052    C
0053          DIMENSION FRACRR(50),XFRAC(50),PERC(9),XPERC(9),XMET(15),XMETF(15)
0054             CHARACTER FILENAME*40
0055             CHARACTER*70 TITLE
0056             DATA PERC/0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9/
0057          DATA XMET/1.,2.,5.,10.,20.,30.,40.,50.,60.,70.,80.,90.,100.,150.,
0058           1200./
0059             WRITE(6,800)
0060      800    FORMAT(/,3X,'TYPE THE NAME OF DATA FILE')
0061             READ(5,'(A70)') FILENAME
0062             OPEN(UNIT=4,FILE=FILENAME,STATUS='OLD')
0063             READ (4,'(A70)')TITLE
0064             READ (4,*) DIAMET
0065             READ (4,*) HEIGHT, CHARGL, BURDEN, SPACIN
0066             READ (4,*) ROCKFA, SPECIG, RWEIST, DACCSD
0067             READ (4,*) NSTAGG, BCL, CCL, SPROK
0068
0069    C
0070    C       ------------------------------------------------------
0071    C       Values are all entered and pre. computations commence
0072    C       ------------------------------------------------------
0073    C
0074             XMASS=(3.141592654*(DIAMET**2)/4000.)*CHARGL*SPECIG
```

```
0075            RSB=SPACIN/BURDEN
0076            VOLPBH=HEIGHT*BURDEN*SPACIN
0077            POWF=XMASS/(SPROK*VOLPBH)
0078      C
0079      C     ------------------------------------------------------
0080      C     Computation of Kuznetsov mean size and Rosin-Rammler 'n'
0081      C     ------------------------------------------------------
0082      C
0083            XBARKP=ROCKFA*((VOLPBH/XMASS)**0.8)*(XMASS**0.1666667)
0084            XBARK=XBARKP*((115/RWEIST)**0.63333)
0085            XNRRP=(2.2-(14*BURDEN/DIAMET))*(1-(DACCSD/BURDEN))
0086            XNRRS=(((1+(SPACIN/BURDEN))/2)**0.5)
0087            XNRRT=(((ABS(BCL-CCL)/CHARGL)+0.1)**0.1)*(CHARGL/HEIGHT)
0088            XNRR=XNRRP*XNRRS*XNRRT
0089            IF(NSTAGG.GE.1)XNRR=XNRR*1.1
0090      C
0091      C     ------------------------------------------------------
0092      C     Computation of Rosin-Rammler characteristic size and set
0093      C     up for final computation of size distribution.
0094      C     ------------------------------------------------------
0095      C
0096            XCRRP=0.69314**(1/XNRR)
0097            XCRR=XBARK/XCRRP
0098            XFIRST=XBARK/16.
0099            DO 10 I=1,9
0100            FRACRR(I)=EXP(-(XFIRST/XCRR)**XNRR)
0101            FRACRR(I)=FRACRR(I)*100.
0102            XFRAC(I)=XFIRST
0103            XFIRST=XFIRST*2.
0104            XPERC(I)=XCRR*((-ALOG(PERC(I)))**(1/XNRR))
0105            PERC(I)=PERC(I)*100.
0106      10    CONTINUE
0107            DO 15 I=1,15
0108            XMETF(I)=100.*(EXP(-(XMET(I)/XCRR)**XNRR))
0109      15    CONTINUE
0110      C
0111      C     ------------------------------------------------------
0112      C     Computations are completed - output results
0113      C     ------------------------------------------------------
```

```
0114    C
0115          WRITE(8,900)
0116     900  FORMAT('1',/,18X,'FRAGMENTATION PREDICTION -  KUZ-RAM METHOD',/)
0117          WRITE(8,901)
0118     901  FORMAT(3X,75(1H-))
0119          WRITE(8,910)TITLE
0120     910  FORMAT(3X,A70,/)
0121          WRITE(8,920)
0122     920  FORMAT(13X,'     SUMMARY OF INPUT INFORMATION')
0123          WRITE(8,930) DIAMET, HEIGHT, CHARGL, BURDEN, SPACIN, XMASS
0124     930  FORMAT(/,3X,'DIAMETER OF BLASTHOLE (mm):',4X,F7.2,2X,
0125         1'BENCH HEIGHT (m):',12X,F5.2,/,3X,'CHARGE LENGTH (m):',15X,F5.2,
0126         22X,'BURDEN (m):',18X,F5.2,/,3X,'SPACING (m):',21X,F5.2,2X,
0127         3'EXPLOSIVE PER HOLE (kg):',4X,F6.2)
0128          WRITE(8,940) ROCKFA,SPECIG,RWEIST,DACCSD,SPROK,VOLPBH
0129     940  FORMAT(3X,'EMPIRICAL ROCK QUALITY FACTOR:',3X,F5.2,2X,
0130         1'S.G. OF EXPLOSIVE:',11X,F5.2,/,3X,'RELATIVE WEIGHT STRENGTH:',7X,
0131         2F6.2,2X,'DRILLING ACCURACY S.D.(m):',2X,F5.2,/,3X,'S.G. OF ROCK:',
0132         320X,F5.2,2X,'VOLUME PER BLASTHOLE(cu.m):',F7.2)
0133          IF(NSTAGG.LT.1)GO TO 20
0134          WRITE(8,950)
0135     950  FORMAT('   STAGGERED DRILLING PATTERN')
0136          GO TO 30
0137     20   WRITE(8,960)
0138     960  FORMAT('   RECTANGULAR DRILLING PATTERN')
0139     30   WRITE(8,901)
0140          WRITE(8,961)
0141     961  FORMAT(/,23X,'COMPUTATION RESULTS')
0142          WRITE(8,970)XBARK,XCRR,XNRR, POWF
0143     970  FORMAT(/,3X,'PREDICTED MEAN FRAGMENT SIZE (cm):',9X,F5.2,
0144         1/,3X,'CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):',2X,F5.2,
0145         2/,3X,'EXPONENT FOR CURVE SHAPE (n)            :',2X,F5.2,
0146         3/,3X,'APPROXIMATE POWDER FACTOR (kg/t)        :',2X,F5.2)
0147          WRITE(8,980)
0148     980  FORMAT(/,3X,'PREDICTED FRAGMENTATION SIZE DISTRIBUTION',/,
0149         15X,'NO.',5X,'DIMENSION (CM)',4X,'PERCENT RETAINED',3X,
0150         2'CUMULATIVE DISTRIBUTION',/)
0151          DO 40 II=1,9
0152          XCUMUL=100.-FRACRR(II)
```

```
0153          WRITE(8,990)II,XFRAC(II),FRACRR(II),XCUMUL
0154     990  FORMAT(5X,I2,10X,F7.2,10X,F7.2,10X,F7.2)
0155     40   CONTINUE
0156          WRITE(8,980)
0157          DO 50 II=9,1,-1
0158          XYCUM=100.-PERC(II)
0159          IJI=10-II
0160          WRITE(8,990)IJI,XPERC(II),PERC(II),XYCUM
0161     50   CONTINUE
0162          WRITE(8,901)
0163          WRITE(8,980)
0164          DO 60 II=1,15
0165          XYMET=100.-XMETF(II)
0166          WRITE(8,990)II,XMET(II),XMETF(II),XYMET
0167     60   CONTINUE
0168          WRITE(8,901)
0169          STOP
0170          END
```

RESULTS FOR SAMPLE INPUT DATA FILE

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

SAMPLE INPUT DATA FILE

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	165.00	BENCH HEIGHT (m):	14.00
CHARGE LENGTH (m):	14.00	BURDEN (m):	3.00
SPACING (m):	3.00	EXPLOSIVE PER HOLE (kg):	239.48
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.30
S.G. OF ROCK:	2.80	VOLUME PER BLASTHOLE(cu.m):	126.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	16.29
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	20.04
EXPONENT FOR CURVE SHAPE (n) :	1.77
APPROXIMATE POWDER FACTOR (kg/t) :	0.68

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.02	99.49	0.51
2	2.04	98.26	1.74
3	4.07	94.20	5.80
4	8.14	81.58	18.42
5	16.29	50.00	50.00
6	32.58	9.44	90.56
7	65.15	0.03	99.97
8	130.30	0.00	100.00
9	260.61	0.00	100.00

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	5.61	90.00	10.00
2	8.58	80.00	20.00
3	11.18	70.00	30.00
4	13.71	60.00	40.00
5	16.29	50.00	50.00
6	19.07	40.00	60.00
7	22.26	30.00	70.00
8	26.23	20.00	80.00
9	32.12	10.00	90.00

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.50	0.50
2	2.00	98.31	1.69
3	5.00	91.77	8.23
4	10.00	74.63	25.37
5	20.00	36.92	63.08
6	30.00	13.00	87.00
7	40.00	3.36	96.64
8	50.00	0.65	99.35
9	60.00	0.10	99.90
10	70.00	0.01	99.99
11	80.00	0.00	100.00
12	90.00	0.00	100.00
13	100.00	0.00	100.00
14	150.00	0.00	100.00
15	200.00	0.00	100.00

APPENDIX B

OPEN-PIT SIMULATION RESULTS

This appendix contains the full results of the test experiments for the case study presented in Chapter 5.1. For brevity, only one size distribution set of values is presented.

CASE 1: BURDEN = 4.5m, ROCK FACTOR = 9.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 6.7m RF = 9.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	4.50
SPACING (m):	10.00	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	9.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	585.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	26.58
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	32.43
EXPONENT FOR CURVE SHAPE (n) :	1.84
APPROXIMATE POWDER FACTOR (kg/t) :	0.24

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.84	0.16
2	2.00	99.41	0.59
3	5.00	96.86	3.14
4	10.00	89.18	10.82
5	20.00	66.33	33.67
6	30.00	42.05	57.95
7	40.00	22.96	77.04
8	50.00	10.87	89.13
9	60.00	4.48	95.52
10	70.00	1.62	98.38
11	80.00	0.51	99.49
12	90.00	0.14	99.86
13	100.00	0.04	99.96
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 2: BURDEN = 4.5, ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 6.7m RF = 10.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	4.50
SPACING (m):	10.00	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	585.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	27.98
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	34.14
EXPONENT FOR CURVE SHAPE (n) :	1.84
APPROXIMATE POWDER FACTOR (kg/t) :	0.24

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.85	0.15
2	2.00	99.46	0.54
3	5.00	97.13	2.87
4	10.00	90.10	9.90
5	20.00	68.83	31.17
6	30.00	45.47	54.53
7	40.00	26.21	73.79
8	50.00	13.27	86.73
9	60.00	5.93	94.07
10	70.00	2.35	97.65
11	80.00	0.82	99.18
12	90.00	0.26	99.74
13	100.00	0.07	99.93
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 3: BURDEN = 4.5m, ROCK FACTOR = 10.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 6.7m RF = 10.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	4.50
SPACING (m):	10.00	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	585.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):		29.38
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):		35.85
EXPONENT FOR CURVE SHAPE (n)	:	1.84
APPROXIMATE POWDER FACTOR (kg/t)	:	0.24

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.86	0.14
2	2.00	99.51	0.49
3	5.00	97.38	2.62
4	10.00	90.91	9.09
5	20.00	71.08	28.92
6	30.00	48.65	51.35
7	40.00	29.41	70.59
8	50.00	15.79	84.21
9	60.00	7.56	92.44
10	70.00	3.24	96.76
11	80.00	1.24	98.76
12	90.00	0.43	99.57
13	100.00	0.13	99.87
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 4: BURDEN = 5.6m, ROCK FACTOR = 9.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 8.3m RF = 9.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	5.60
SPACING (m):	12.30	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	9.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	895.44

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	37.36
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	45.63
EXPONENT FOR CURVE SHAPE (n) :	1.83
APPROXIMATE POWDER FACTOR (kg/t) :	0.16

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.91	0.09
2	2.00	99.68	0.32
3	5.00	98.28	1.72
4	10.00	94.01	5.99
5	20.00	80.23	19.77
6	30.00	62.91	37.09
7	40.00	45.59	54.41
8	50.00	30.65	69.35
9	60.00	19.16	80.84
10	70.00	11.17	88.83
11	80.00	6.08	93.92
12	90.00	3.09	96.91
13	100.00	1.48	98.52
14	150.00	0.01	99.99
15	200.00	0.00	100.00

CASE 5: Burden = 5.6m ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 8.3m RF = 10.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	5.60
SPACING (m):	12.30	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	895.44

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	39.33
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	48.03
EXPONENT FOR CURVE SHAPE (n) :	1.83
APPROXIMATE POWDER FACTOR (kg/t) :	0.16

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.92	0.08
2	2.00	99.71	0.29
3	5.00	98.43	1.57
4	10.00	94.53	5.47
5	20.00	81.83	18.17
6	30.00	65.58	34.42
7	40.00	48.92	51.08
8	50.00	34.08	65.92
9	60.00	22.23	77.77
10	70.00	13.60	86.40
11	80.00	7.82	92.18
12	90.00	4.23	95.77
13	100.00	2.15	97.85
14	150.00	0.03	99.97
15	200.00	0.00	100.00

CASE 6: BURDEN = 5.6m, ROCK FACTOR = 10.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 8.3m RF = 10.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	5.60
SPACING (m):	12.30	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	895.44

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	41.30
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	50.43
EXPONENT FOR CURVE SHAPE (n) :	1.83
APPROXIMATE POWDER FACTOR (kg/t) :	0.16

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.92	0.08
2	2.00	99.73	0.27
3	5.00	98.57	1.43
4	10.00	94.99	5.01
5	20.00	83.25	16.75
6	30.00	68.00	32.00
7	40.00	52.01	47.99
8	50.00	37.37	62.63
9	60.00	25.28	74.72
10	70.00	16.13	83.87
11	80.00	9.72	90.28
12	90.00	5.54	94.46
13	100.00	2.99	97.01
14	150.00	0.06	99.94
15	200.00	0.00	100.00

CASE 7: BURDEN = 6.4, ROCK FACTOR = 9.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 9.5m RF = 9.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	6.40
SPACING (m):	14.10	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	9.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	1173.12

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	46.38
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	56.69
EXPONENT FOR CURVE SHAPE (n) :	1.82
APPROXIMATE POWDER FACTOR (kg/t) :	0.12

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.94	0.06
2	2.00	99.78	0.22
3	5.00	98.82	1.18
4	10.00	95.87	4.13
5	20.00	86.12	13.88
6	30.00	73.12	26.88
7	40.00	58.91	41.09
8	50.00	45.15	54.85
9	60.00	32.99	67.01
10	70.00	23.01	76.99
11	80.00	15.34	84.66
12	90.00	9.78	90.22
13	100.00	5.98	94.02
14	150.00	0.27	99.73
15	200.00	0.00	100.00

CASE 8: BURDEN = 6.4m, ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 9.5m RF = 10.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	6.40
SPACING (m):	14.10	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	1173.12

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):		48.82
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):		59.68
EXPONENT FOR CURVE SHAPE (n)	:	1.82
APPROXIMATE POWDER FACTOR (kg/t)	:	0.12

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.94	0.06
2	2.00	99.80	0.20
3	5.00	98.92	1.08
4	10.00	96.23	3.77
5	20.00	87.28	12.72
6	30.00	75.20	24.80
7	40.00	61.76	38.24
8	50.00	48.48	51.52
9	60.00	36.42	63.58
10	70.00	26.24	73.76
11	80.00	18.14	81.86
12	90.00	12.04	87.96
13	100.00	7.69	92.31
14	150.00	0.46	99.54
15	200.00	0.01	99.99

CASE 9: BURDEN = 6.4m, ROCK FACTOR = 10.5

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

OPEN PIT SIMULATION Pattern = 9.5m RF = 10.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	318.00	BENCH HEIGHT (m):	13.00
CHARGE LENGTH (m):	10.50	BURDEN (m):	6.40
SPACING (m):	14.10	EXPLOSIVE PER HOLE (kg):	708.85
EMPIRICAL ROCK QUALITY FACTOR:	10.50	S.G. OF EXPLOSIVE:	0.85
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	5.00	VOLUME PER BLASTHOLE(cu.m):	1173.12

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	51.26
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	62.66
EXPONENT FOR CURVE SHAPE (n) :	1.82
APPROXIMATE POWDER FACTOR (kg/t) :	0.12

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.95	0.05
2	2.00	99.81	0.19
3	5.00	99.01	0.99
4	10.00	96.55	3.45
5	20.00	88.30	11.70
6	30.00	77.04	22.96
7	40.00	64.35	35.65
8	50.00	51.56	48.44
9	60.00	39.70	60.30
10	70.00	29.40	70.60
11	80.00	20.98	79.02
12	90.00	14.42	85.58
13	100.00	9.57	90.43
14	150.00	0.73	99.27
15	200.00	0.02	99.98

APPENDIX C

BLASTHOLE STOPING SIMULATION RESULTS

This appendix contains the full results of the test experiments for the case study presented in Chapter 5.2. For brevity, only one size distribution set of values is presented.

CASE 1: W = 0.0, ROCK FACTOR = 8

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 8. W = 0.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	8.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	29.35
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	35.61
EXPONENT FOR CURVE SHAPE (n) :	1.90
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.89	0.11
2	2.00	99.58	0.42
3	5.00	97.61	2.39
4	10.00	91.39	8.61
5	20.00	71.54	28.46
6	30.00	48.55	51.45
7	40.00	28.75	71.25
8	50.00	14.91	85.09
9	60.00	6.80	93.20
10	70.00	2.73	97.27
11	80.00	0.97	99.03
12	90.00	0.30	99.70
13	100.00	0.08	99.92
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 2: W = 0.0, ROCK FACTOR = 9.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 9. W = 0.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	9.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	33.02
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	40.06
EXPONENT FOR CURVE SHAPE (n) :	1.90
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.91	0.09
2	2.00	99.66	0.34
3	5.00	98.08	1.92
4	10.00	93.05	6.95
5	20.00	76.50	23.50
6	30.00	56.11	43.89
7	40.00	36.90	63.10
8	50.00	21.83	78.17
9	60.00	11.64	88.36
10	70.00	5.61	94.39
11	80.00	2.45	97.55
12	90.00	0.97	99.03
13	100.00	0.35	99.65
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 3: W = 0.0, ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 10. W = 0.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	36.69
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	44.51
EXPONENT FOR CURVE SHAPE (n) :	1.90
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.93	0.07
2	2.00	99.72	0.28
3	5.00	98.43	1.57
4	10.00	94.27	5.73
5	20.00	80.30	19.70
6	30.00	62.30	37.70
7	40.00	44.20	55.80
8	50.00	28.75	71.25
9	60.00	17.18	82.82
10	70.00	9.45	90.55
11	80.00	4.79	95.21
12	90.00	2.24	97.76
13	100.00	0.97	99.03
14	150.00	0.00	100.00
15	200.00	0.00	100.00

CASE 4: W = 0.5, ROCK FACTOR = 8

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 8. W = 0.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	8.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	29.35
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	36.78
EXPONENT FOR CURVE SHAPE (n) :	1.62
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.71	0.29
2	2.00	99.12	0.88
3	5.00	96.17	3.83
4	10.00	88.65	11.35
5	20.00	68.96	31.04
6	30.00	48.76	51.24
7	40.00	31.78	68.22
8	50.00	19.26	80.74
9	60.00	10.91	89.09
10	70.00	5.81	94.19
11	80.00	2.91	97.09
12	90.00	1.38	98.62
13	100.00	0.62	99.38
14	150.00	0.01	99.99
15	200.00	0.00	100.00

CASE 5: W = 0.5, ROCK FACTOR = 9.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 9. W = 0.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	9.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	33.02
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	41.37
EXPONENT FOR CURVE SHAPE (n) :	1.62
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.76	0.24
2	2.00	99.27	0.73
3	5.00	96.83	3.17
4	10.00	90.53	9.47
5	20.00	73.57	26.43
6	30.00	55.26	44.74
7	40.00	38.81	61.19
8	50.00	25.66	74.34
9	60.00	16.05	83.95
10	70.00	9.54	90.46
11	80.00	5.40	94.60
12	90.00	2.91	97.09
13	100.00	1.51	98.49
14	150.00	0.03	99.97
15	200.00	0.00	100.00

CASE 6: W = 0.5, ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 10. W = 0.5

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	0.50
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	36.69
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	45.97
EXPONENT FOR CURVE SHAPE (n) :	1.62
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.80	0.20
2	2.00	99.39	0.61
3	5.00	97.32	2.68
4	10.00	91.96	8.04
5	20.00	77.21	22.79
6	30.00	60.67	39.33
7	40.00	45.04	54.96
8	50.00	31.78	68.22
9	60.00	21.41	78.59
10	70.00	13.80	86.20
11	80.00	8.54	91.46
12	90.00	5.08	94.92
13	100.00	2.91	97.09
14	150.00	0.11	99.89
15	200.00	0.00	100.00

CASE 7: W = 1.0, ROCK FACTOR = 8.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 8. W = 1.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	8.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	1.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	29.35
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	38.47
EXPONENT FOR CURVE SHAPE (n) :	1.35
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.29	0.71
2	2.00	98.19	1.81
3	5.00	93.89	6.11
4	10.00	85.11	14.89
5	20.00	66.21	33.79
6	30.00	48.97	51.03
7	40.00	34.85	65.15
8	50.00	24.03	75.97
9	60.00	16.12	83.88
10	70.00	10.55	89.45
11	80.00	6.76	93.24
12	90.00	4.24	95.76
13	100.00	2.61	97.39
14	150.00	0.18	99.82
15	200.00	0.01	99.99

CASE 8: W = 1.0, ROCK FACTOR = 9.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 9. W = 1.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	9.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	1.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	33.02
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	43.28
EXPONENT FOR CURVE SHAPE (n) :	1.35
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.39	0.61
2	2.00	98.46	1.54
3	5.00	94.76	5.24
4	10.00	87.15	12.85
5	20.00	70.36	29.64
6	30.00	54.40	45.60
7	40.00	40.71	59.29
8	50.00	29.65	70.35
9	60.00	21.09	78.91
10	70.00	14.70	85.30
11	80.00	10.05	89.95
12	90.00	6.76	93.24
13	100.00	4.47	95.53
14	150.00	0.46	99.54
15	200.00	0.04	99.96

CASE 9: W = 1.0, ROCK FACTOR = 10.0

FRAGMENTATION PREDICTION - KUZ-RAM METHOD

BLASTHOLE STOPING SIMULATION A = 10. W = 1.0

SUMMARY OF INPUT INFORMATION

DIAMETER OF BLASTHOLE (mm):	127.00	BENCH HEIGHT (m):	30.00
CHARGE LENGTH (m):	30.00	BURDEN (m):	3.50
SPACING (m):	4.00	EXPLOSIVE PER HOLE (kg):	304.02
EMPIRICAL ROCK QUALITY FACTOR:	10.00	S.G. OF EXPLOSIVE:	0.80
RELATIVE WEIGHT STRENGTH:	100.00	DRILLING ACCURACY S.D. (m):	1.00
S.G. OF ROCK:	4.00	VOLUME PER BLASTHOLE(cu.m):	420.00

RECTANGULAR DRILLING PATTERN

COMPUTATION RESULTS

PREDICTED MEAN FRAGMENT SIZE (cm):	36.69
CHARACTERISTIC SIZE (ROSIN-RAMMLER) (cm):	48.09
EXPONENT FOR CURVE SHAPE (n) :	1.35
APPROXIMATE POWDER FACTOR (kg/t) :	0.18

PREDICTED FRAGMENTATION SIZE DISTRIBUTION

NO.	DIMENSION (CM)	PERCENT RETAINED	CUMULATIVE DISTRIBUTION
1	1.00	99.47	0.53
2	2.00	98.66	1.34
3	5.00	95.44	4.56
4	10.00	88.76	11.24
5	20.00	73.73	26.27
6	30.00	58.99	41.01
7	40.00	45.88	54.12
8	50.00	34.85	65.15
9	60.00	25.94	74.06
10	70.00	18.97	81.03
11	80.00	13.64	86.36
12	90.00	9.67	90.33
13	100.00	6.76	93.24
14	150.00	0.94	99.06
15	200.00	0.10	99.90